TECHNICAL NOTES

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

No. 569

# BOOSTED PERFORMANCE OF A COMPRESSION-IGNITION ENGINE WITH A DISPLACER PISTON

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Washington
May 1936

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## SUMMARY

Performance tests were made using a rectangular displacer arranged so that the combustion air was forced through equal passages at either end of the displacer into the vertical-disk combustion chamber of a single-cylinder, four-stroke-cycle compression-ignition test engine. After making tests to determine optimum displacer height, shape, and fuel-spray arrangement, engine-performance tests were made at 1,500 and 2,000 r.p.m. for a range of boost pressures from zero to 20 inches of mercury and for maximum cylinder pressures up to 1,150 pounds per square inch. The engine operation for boosted conditions was very smooth, there being no combustion shock even at the highest maximum cylinder pressures. Indicated mean effective pressures of 240 pounds per square inch for fuel consumptions of 0.39 pound per horsepower-hour have been readily reproduced during routine testing at 2,000 r.p.m. at a boost pressure of 20 inches of mercury.

## INTRODUCTION

This investigation is part of a general research on the performance possibilities and characteristics of a particular displacer-piston combustion chamber (reference 1). In this combustion chamber a rectangular displacer generates, during the last part of the compression stroke, a forced symmetrical air flow through a passage at each end of the displacer resulting in rapid rotational air movement or turbulence within the vertical-disk combustion chamber. The air movement persists, during the injection of fuel from multiple orifices, proportioned according to the volume of air to be served, so that fuel and air mixing is effected both by direct injection and by forced and residual air movement.

Reference 1 records the effects of passage arrangement and air-flow velocity on unboosted engine performance at 1,500 r.p.m. The present note contains results of engine-performance tests up to limits of 2,000 r.p.m., 20 inches of mercury boost pressure, and 1,150 pounds per square inch maximum cylinder pressure.

This work was done during 1935 and early 1936 in the engine-research laboratory at Langley Field, Va.

## APPARATUS

Figures 1 and 2 show the combustion chamber, fuel-spray arrangement, and assembly of equipment used in obtaining the performance results at 2,000 r.p.m. Test results have not been corrected to standard atmospheric temperature and pressure owing to absence of an accepted method of correction. The test engine and necessary auxiliaries are the same as those used in the previous displacer tests (reference 1) except for minor changes as noted in the text; however, for convenience of reference the more important parts of the test unit and some test conditions are noted:

| | |
|---|---|
| Engine . . . . . . . . . . . | Single-cylinder 4-stroke-cycle, 5-inch bore, 7-inch stroke. |
| Engine speed . . . . . . . . | 1,500 and 2,000 r.p.m. |
| Compression ratios . . . | 15.2 and 14.6. |
| Valve timing . . . . . . | See figure 3. (Optimum for 2,000 r.p.m.) |
| Fuel . . . . . . . . . . | Auto diesel fuel, 0.847 specific gravity, 41 seconds Saybolt Universal viscosity at 80° F. |
| Fuel-injection pump . . . | N.A.C.A. cam-operated, constant-stroke type. |
| Fuel-injection valve . . . | N.A.C.A. automatic, spring-loaded to 3,500 lb./sq.in. |
| Power measurement and absorption . . . . . . | Electric dynamometer unit. |

| | |
|---|---|
| Supercharger . . . . . . . . | 4-inch Roots-type blower, separately driven. |
| Operating temperatures . . | Water and oil (out) 170° F., inlet-air (unboosted) 95° F., (boosted) 80° to 120° F. |
| Air and fuel consumption measurements . . . . . | Electrically operated stop watches and revolution counters. |
| Maximum cylinder pressure indicators . . . . . . | Farnboro and trapped-pressure type. |
| Full load . . . . . . . . . | Air-fuel ratio of 14.5 (no excess air). |

## TEST RESULTS AND DISCUSSION

### 1,500 r.p.m.

Prior to obtaining the engine performance presented in this report, work was done to develop further the combustion chamber and fuel spray to optimum conditions. Using the two-passage arrangement and areas recorded in reference 1 as optimum for 1,500 r.p.m., the displacer height was varied, thus varying the timing of the forced air flow. A height such that the displacer entered the throat at 43° B.T.C. gave the maximum brake performance and was accordingly adopted.

The air-flow direction and speed were varied by using different displacer shapes. The ends of the displacer were sloped so as to cause decreasing passage areas with increasing air-flow speeds as the piston approached top center. Although this shape made the maximum air-flow speed occur nearer top center and nearer the injection time the engine performance was adversely affected. Undercutting the displacer ends at the base to make appreciable outward slopes and air flow did, however, cause a slight improvement in engine performance. In general, directing the air flow toward the center of the combustion chamber was detrimental to fuel and air mixing; whereas directing the air flow tangentially to the chamber was helpful.

Brief tests were made with the combustion chamber throat lengthened to obtain a compression ratio of 12.6, the object being to increase the ignition lag and thus allow more time for fuel and air mixing. Inferior engine performance, however, showed that although the ignition lag was increased the fuel and air mixing must have been inferior, probably owing to the inaccessibility of the air in the lengthened combustion chamber.

In order to determine the fuel-spray requirements for this combustion chamber, an extensive series of nozzles was tried; namely, 2-, 3-, 4-, 5-, 6-, and 7-orifice nozzles, as well as slit and impinging-jets nozzles. It was found that the optimum fuel spray (fig. 1) was given by a multiple-orifice nozzle having six orifices in one plane, the areas of which were proportioned according to the volume of air each was to serve, as in the case of the quiescent combustion chamber. (See reference 2.) There is no sacrifice in performance, however, if the diameter of the smallest orifices is increased from 0.008 to 0.010 inch.

As a conclusion to the work at 1,500 r.p.m., using the straight-side displacer shape, the engine performance was investigated for boost pressures from 0 to 10-1/4 inches of mercury while the maximum cylinder pressure at full load was held constant at 880 pounds per square inch by retarding the injection advance angle with each increase in boost pressure. The results of these tests are presented in figure 4 for comparison with the later results at 2,000 r.p.m.

## 2,000 r.p.m. - Unboosted

<u>Preliminary tests</u>.- Motoring and power tests were made at 2,000 r.p.m. with the same valve timing, induction and exhaust systems that were optimum at 1,500 r.p.m. Lower values of volumetric efficiency indicated the need for a change in the valve timing and inlet and exhaust piping. The lengths of intake and exhaust pipes found to be optimum for boosted and unboosted operation at 2,000 r.p.m. are indicated in figure 2. A time-area diagram of the valve timing adopted after boosted and unboosted trials is shown in figure 3. A moderate amount of valve overlap was used to improve clearance scavenging. An aluminum-alloy piston with the displacer cast integral was used for the 1,500 r.p.m. tests. During the preliminary tests at 2,000 r.p.m., the corners of the displacer were

badly burned. The top half of the damaged displacer was machined off and a stainless steel cap, held on by monel metal bolts (fig. 1), was used. No further trouble was experienced from burning of the displacer. The higher temperature of the steel cap at 2,000 r.p.m. did not influence the engine performance because test results at speeds up to 1,800 r.p.m. were the same whether the displacer was cast integral or had the steel cap.

In order to decrease the pumping losses the passage throat was widened from the dotted to the solid outline shown in figure 1, causing an increase of 63 percent in the area of the two passages formed with the displacer in the throat. This increase in passage size decreased the compression ratio from 15.2 to 14.6. Subsequent tests showed a slight decrease in friction mean effective pressure, no appreciable change in volumetric efficiency, but a considerable improvement in both brake and indicated power and economy. The new passage size (31/64 inch by 7/8 inch, instead of 19/64 inch by 7/8 inch) was indicated by tests with larger and smaller passages to be optimum for 2,000 r.p.m. and was used in obtaining the performance data that follow. With the widened throat the air flowed tangentially into the chamber so that the undercut displacer gave no better performance than the flat-end shape (fig. 1), which was accordingly used.

Variable engine speed and i.a.a.- Figure 5 shows the effect of engine speed on cylinder-air charging and engine performance at full-load air-fuel ratio and 880 pounds per square inch maximum cylinder pressure. The increase in indicated mean effective pressure with speed is noteworthy although the valve timing and inlet and exhaust piping favored the higher speed range. The 12-percent increase in volumetric efficiency does not account for all of the 19-percent increase in mean effective pressure; it more likely results from a combination of volumetric efficiency, air-flow speed, and scavenging.

Figure 6 shows the effect of injection advance angle on maximum cylinder pressure, mean effective pressure, and fuel economy at an air-fuel ratio of 14.8. (In the calculation of air-fuel ratio, the engine was charged with all the air inducted.) Note the nearly uniform increase in maximum cylinder pressure and power output and the decrease in fuel consumption as the injection advance angle is increased. There was little, if any, combustion knock even at the highest cylinder pressure.

2,000 r.p.m. - Boosted

Variable i.a.a.- Figure 7 shows results using a boost pressure of 7.5 inches of mercury. The trends of the curves are the same as those in figure 6 but the maximum cylinder pressures and mean effective pressures are higher for the boosted engine, there being little or no difference in specific fuel consumption. For equal injection advance angles the higher compression pressure of the boosted air charge resulted in an increase of about 100 pounds per square inch in maximum cylinder pressures. The weight of the air charge was estimated from the measured volume inducted at no boost and the air density under boost conditions, the loss incurred by valve overlap and boost pressure not being considered. As the power to deliver the intake air at boost pressure has not been measured the brake performance results are presented on a gross basis.

Variable fuel quantity.- Figure 8 shows the results of variable fuel quantity tests up to 15 inches of mercury boost pressure. The regular test points are omitted from the curves to save confusion. One point is included from a test at 20 inches of mercury boost pressure at which a gross brake mean effective pressure of 200 pounds per square inch was obtained at a gross fuel consumption of 0.47 pound per brake horsepower-hour. At a slightly higher cylinder pressure, a brake mean effective pressure of 208 pounds per square inch was obtained. Note the increase in mean effective pressure and decrease in fuel consumption at 15 inches of mercury boost pressure for an increase in maximum cylinder pressure from 1,010 to 1,060 pounds per square inch. Comparing figure 4 with figure 8 shows that the results at 2,000 r.p.m. at somewhat higher maximum cylinder pressures were nearly as good as those at 1,500 r.p.m. For both speeds the operation became exceptionally smooth with increasing boost pressure. Exhaust gases were observed in the room as they issued from a hole in the exhaust pipe located about 10 inches from the exhaust valve. The point at which haze appeared in the exhaust is indicated on the performance curves.

Variable boost pressure.- Figure 9 shows how the ratio of maximum cylinder pressure to compression pressure decreased as the boost pressure was increased. If the ratio for the unboosted test were maintained for the boosted tests, the maximum cylinder pressures would be considerably higher and the performance values correspondingly higher (see figs. 5 and 6); at 20 inches of mercury boost pressure the estimated maximum cylinder pressure would be 1,450 pounds per square inch. The rate of pressure rise would, however, probably be considerably lower than at no boost, owing to the decrease in ignition lag with increase in boost pressure. Thornycroft (reference 3) found that the period of ignition lag is very nearly inversely proportional to the absolute pressure of induction. Thus, the full value of boosting is not realized unless the ratio of maximum cylinder pressure to compression pressure is maintained constant.

It may be noted that the trend of the f.m.e.p. curve is downward as the boost pressure is increased. The slope of this curve depends upon the amount of work done upon the cylinder gases when they are forced through the flow passages as well as upon the boost pressure. In order to maintain low pumping losses, the flow passages should be no smaller than those required for the optimum air-flow speed in the combustion chamber. The calculated air speed, 308 feet per second for these tests, was about 16 percent less than the optimum for the 1,500 r.p.m. tests (reference 1), owing to the use of flow passages of 31/64 by 7/8 inch instead of 19/64 by 7/8 inch.

Indicator cards.- The indicator cards of figure 10, although taken with the narrow throat and 15.2 compression ratio, show how the boosted pressure time card is affected by injection advance angle. In card (a) the injection started at top center. It may be noted that the explosion pressure is lower than the compression pressure, whereas in card (b) with a $2^{\circ}$ i.a.a., the explosion pressure is just equal to the compression pressure giving a flat top or constant-pressure card for about $20^{\circ}$. In card (c) the i.a.a. is $10^{\circ}$ and the maximum cylinder pressure is nearly 1,150 pounds per square inch. With an injection period of 28 crank degrees and such small injection advance angles it is inevitable that there would be considerable late burning on the expansion stroke, especially for cards (a) and (b). This condition is shown in poor engine performance and a flaming and smoking exhaust. The constant-pressure card (fig. 10(b)) is inefficient owing to burning throughout the expansion stroke. It does, however, encourage further development toward a high-speed compression-ignition engine operating according to the diesel cycle with its attendant efficiencies and economies.

## CONCLUSIONS

1. Best engine performance at 1,500 r.p.m. was obtained with a rectangular displacer so designed that it entered the combustion chamber 43° before top center and directed the air flow tangentially into the chamber.

2. At 2,000 r.p.m. better engine performance was obtained at a calculated air-flow speed 5 times the linear speed of the crankpin rather than 8 times, which was optimum at 1,500 r.p.m.

3. Increasing the inlet pressure decreases the ignition lag and consequently the rate of pressure rise in the cylinder, which results in increasing smoothness of operation.

4. In order to obtain power in proportion to the boosted induction pressure with the pressure-rise type of combustion, it is necessary that the maximum cylinder pressure be increased in proportion to the compression pressure.

5. Indicated mean effective pressures of 240 pounds per square inch and fuel consumptions of 0.39 pound per horsepower-hour have been readily reproduced during routine testing at 2,000 r.p.m. and 20 inches of mercury boost pressure.

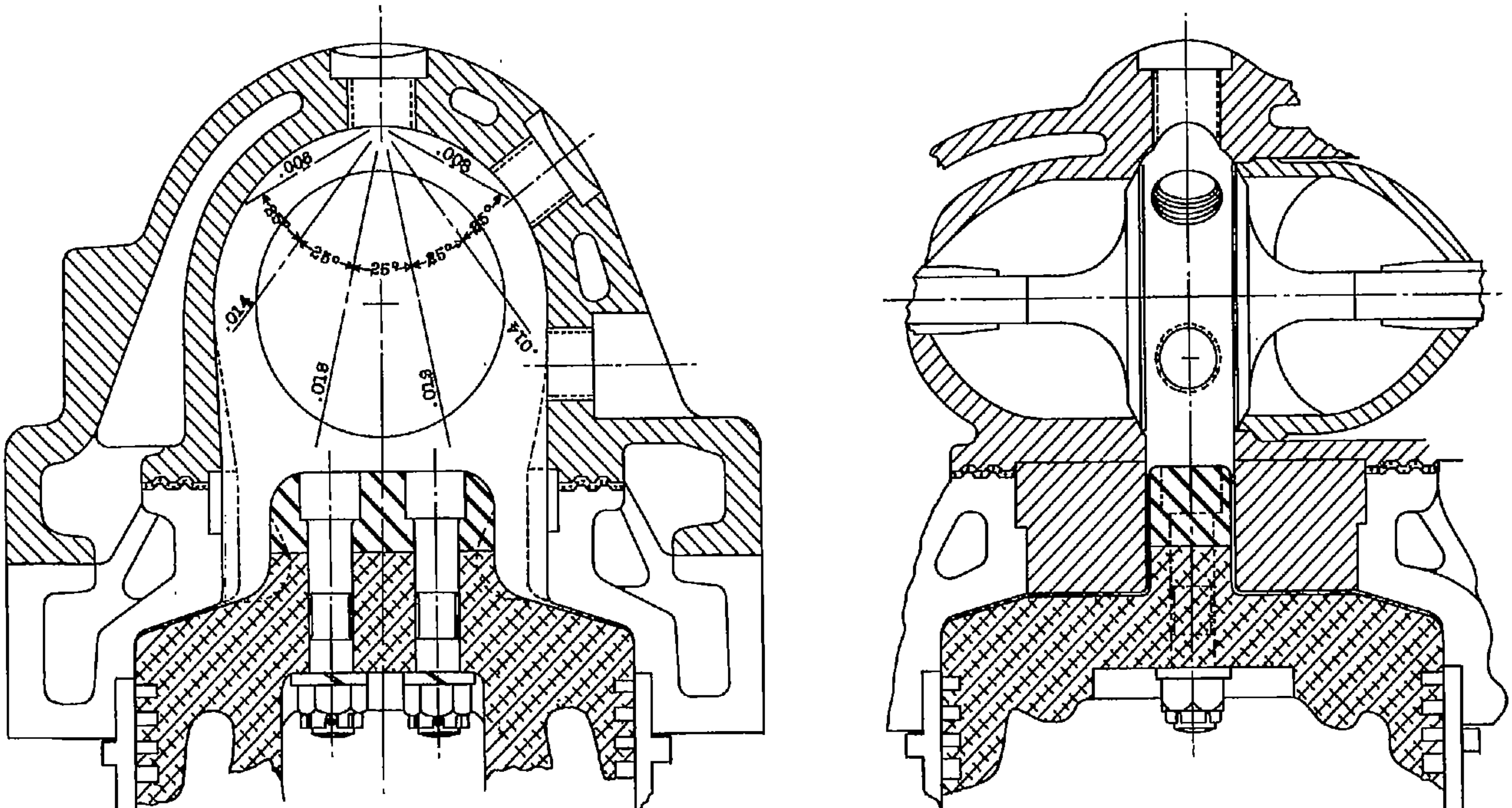
Langley Memorial Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., May 11, 1936.

REFERENCES

1. Moore, C. S., and Foster, H. H.: Performance Tests of a Single-Cylinder Compression-Ignition Engine with a Displacer Piston. T.N. No. 518, N.A.C.A., 1935.

2. Spanogle, J. A., and Foster, H. H.: Basic Requirements of Fuel-Injection Nozzles for Quiescent Combustion Chambers. T.N. No. 382, N.A.C.A., 1931.

3. Thornycroft, O.: The General Question of Supercharging. I. A. E. Journal (British), December 1935, pp. 21-36.




(Side)

(End)

Relative fuel spray lengths for i.a.a. of 10° B.T.C.
(Orifice diameters indicated)

Figure 1.- Combustion chamber.

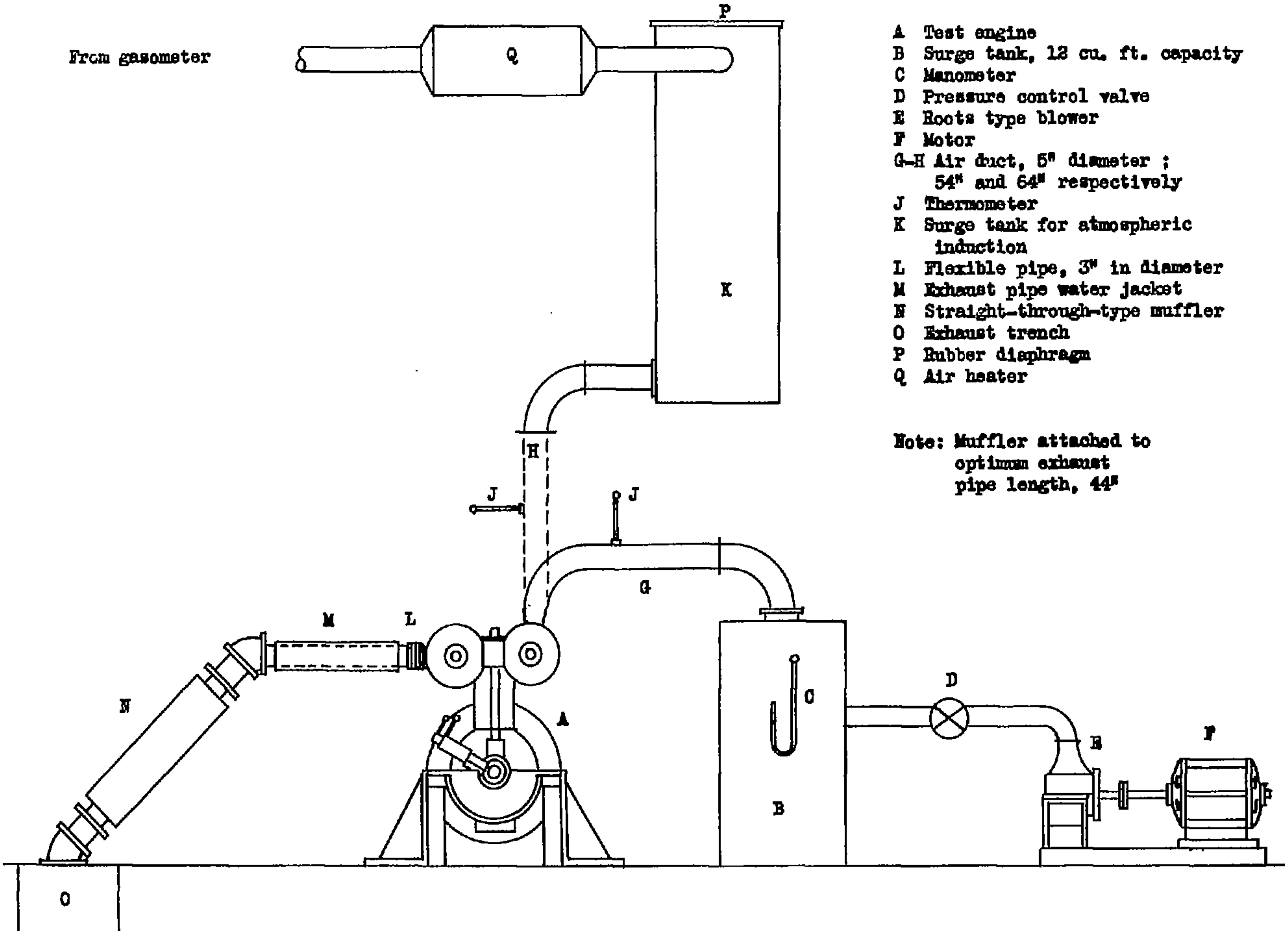



Figure 2. - Diagrammatic representation of air systems for atmospheric induction and boosting

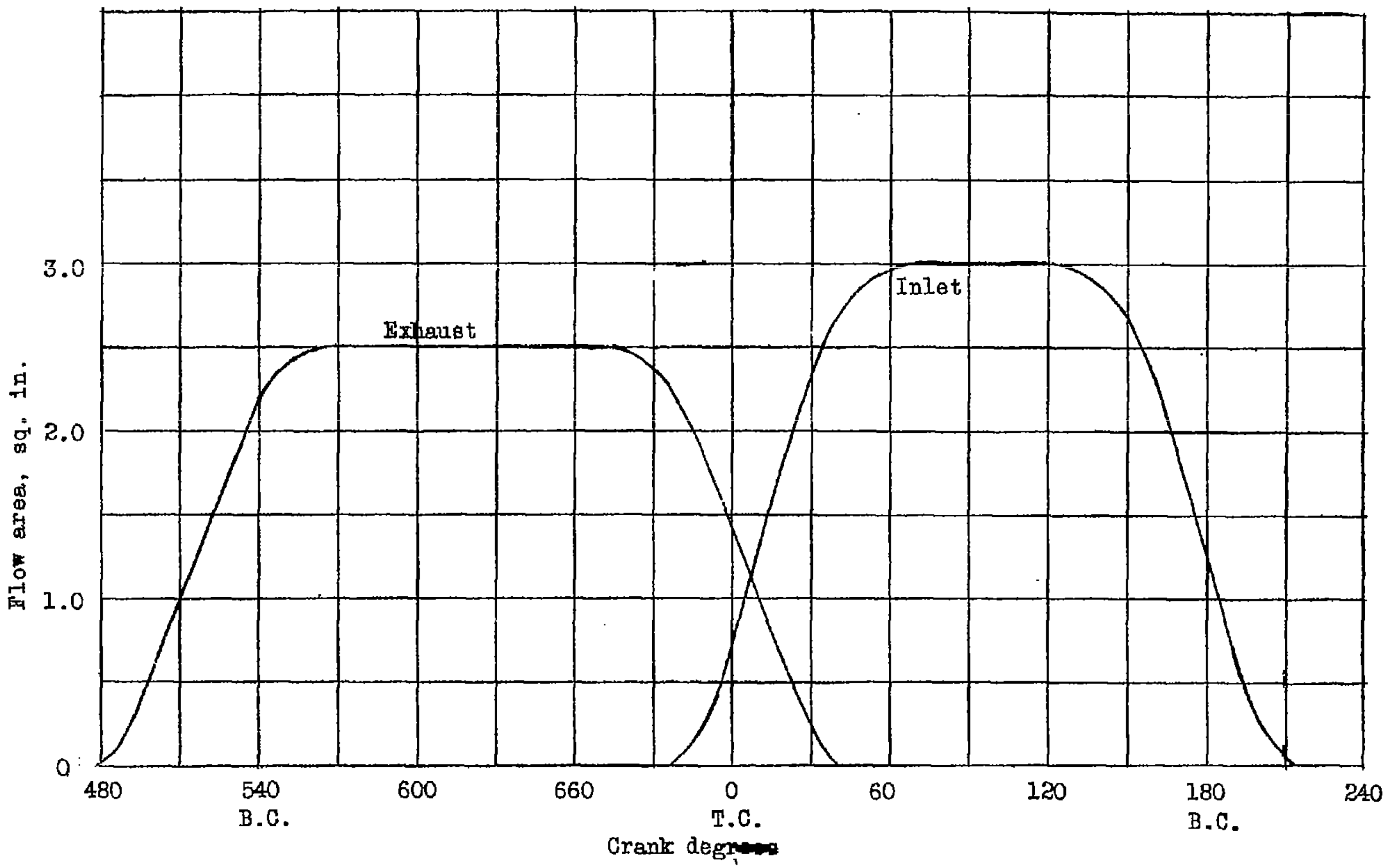



Figure 3.- Valve time-area diagrams.

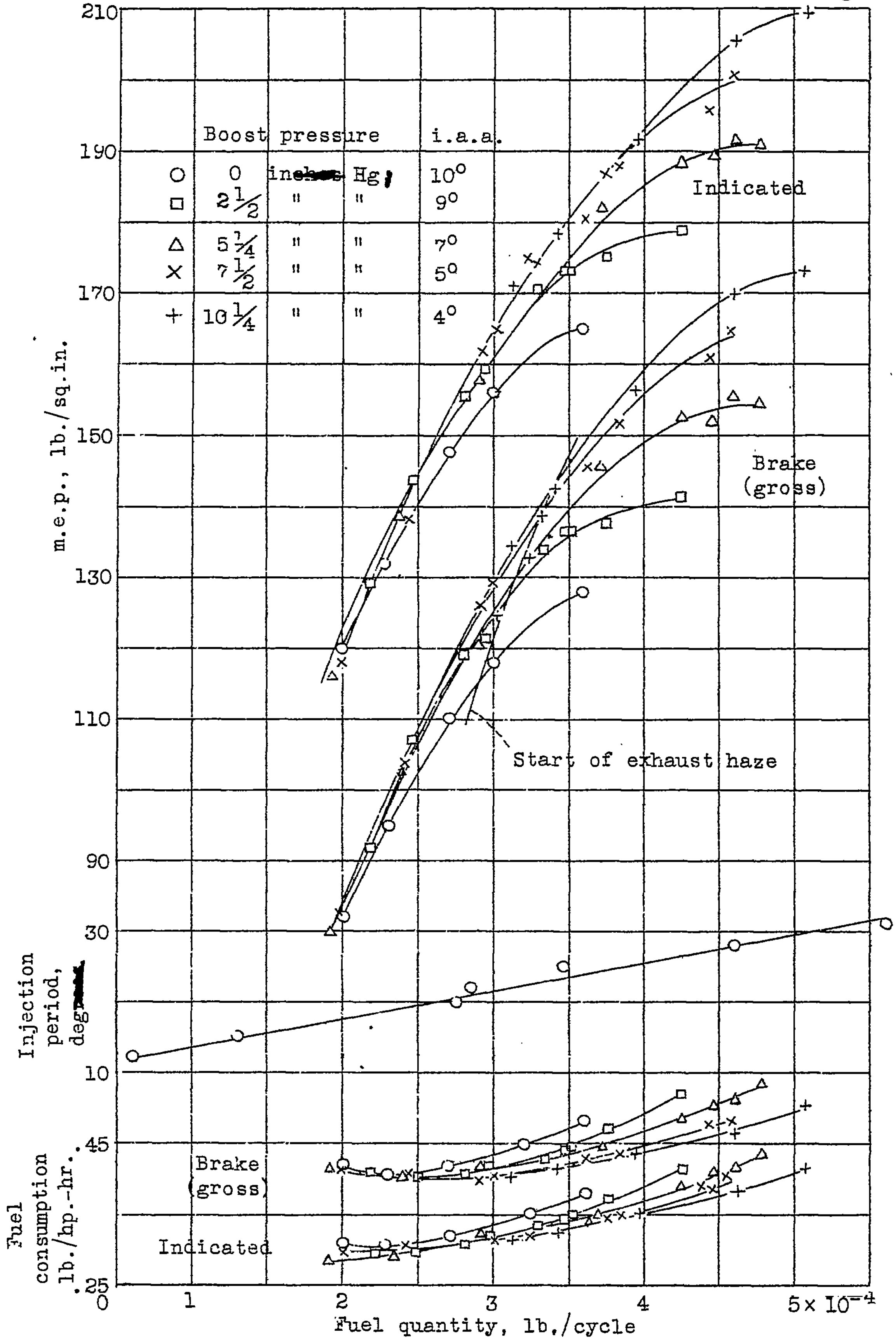



Figure 4.- Boosted engine performance; 1,500 r.p.m.; compression ratio, 15.2; maximum cylinder pressure, 880 lb./sq.in.

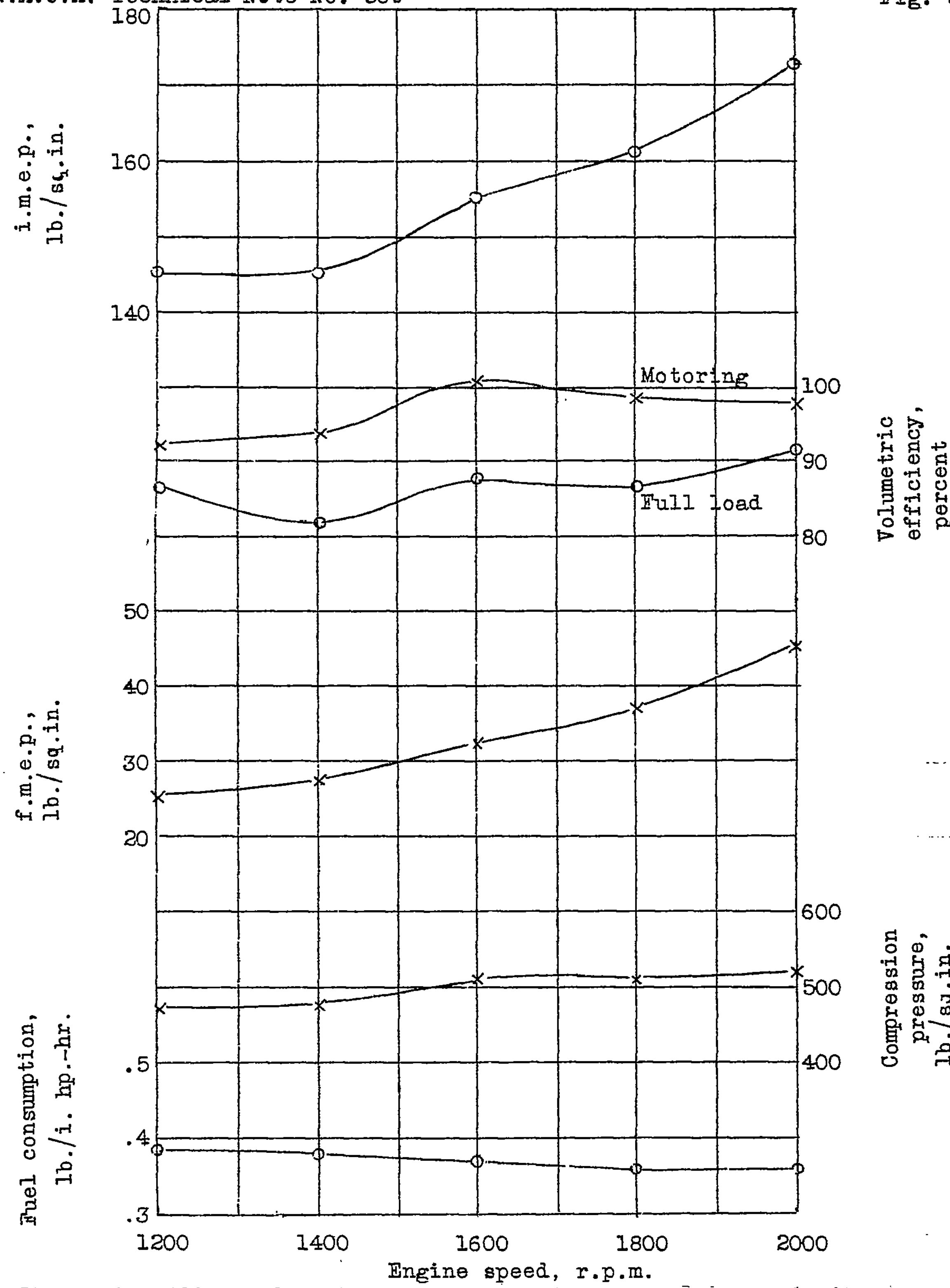



Figure 5.- Effect of engine speed on performance. Unboosted. Air-fuel ratio, 14.5; Compression ratio, 14.6; Maximum cylinder pressure, 880 lb./sq.in.

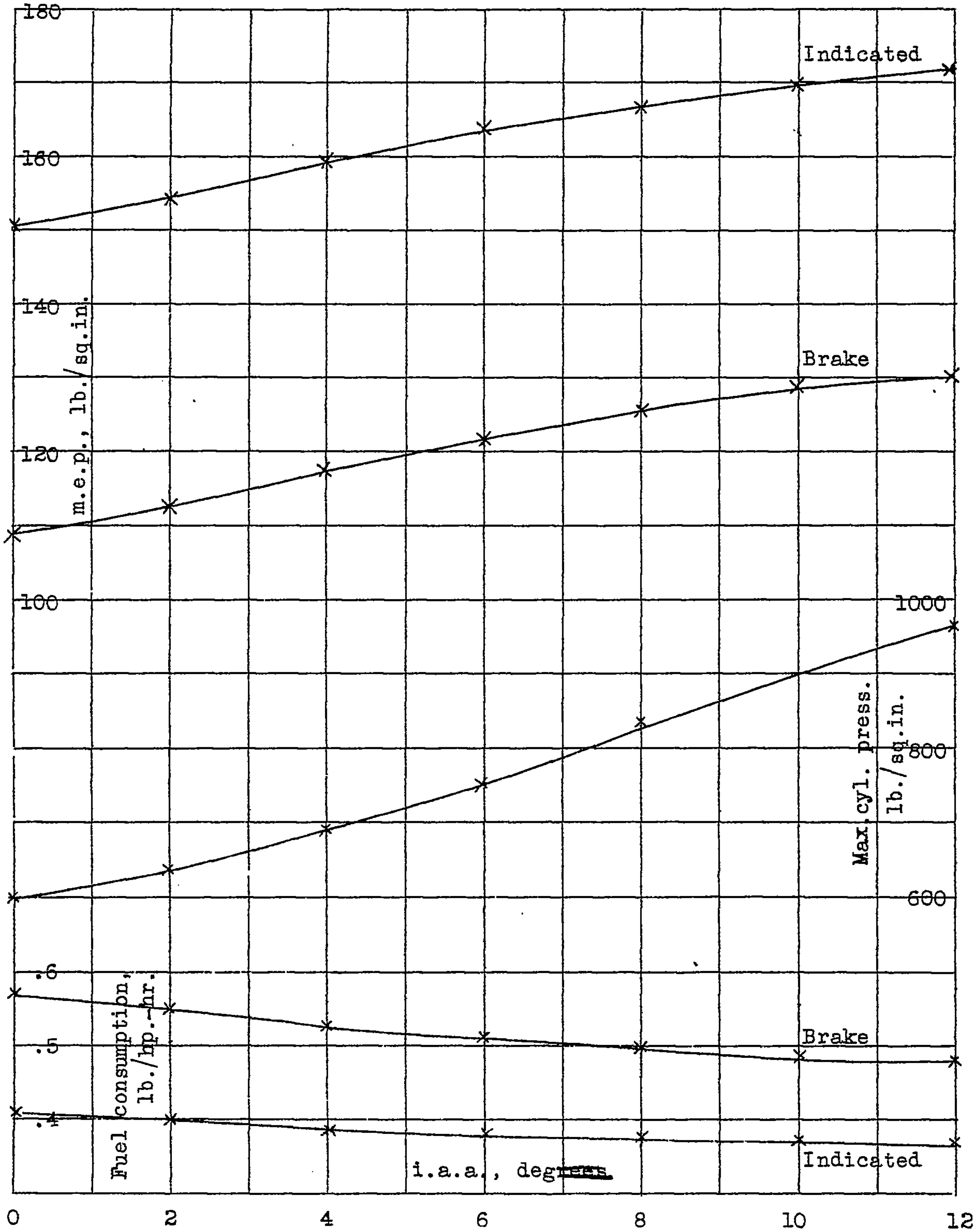



Figure 6.- Effect of injection advance angle on engine performance. 2000 r.p.m.; air-fuel ratio, 14.8; No boost.

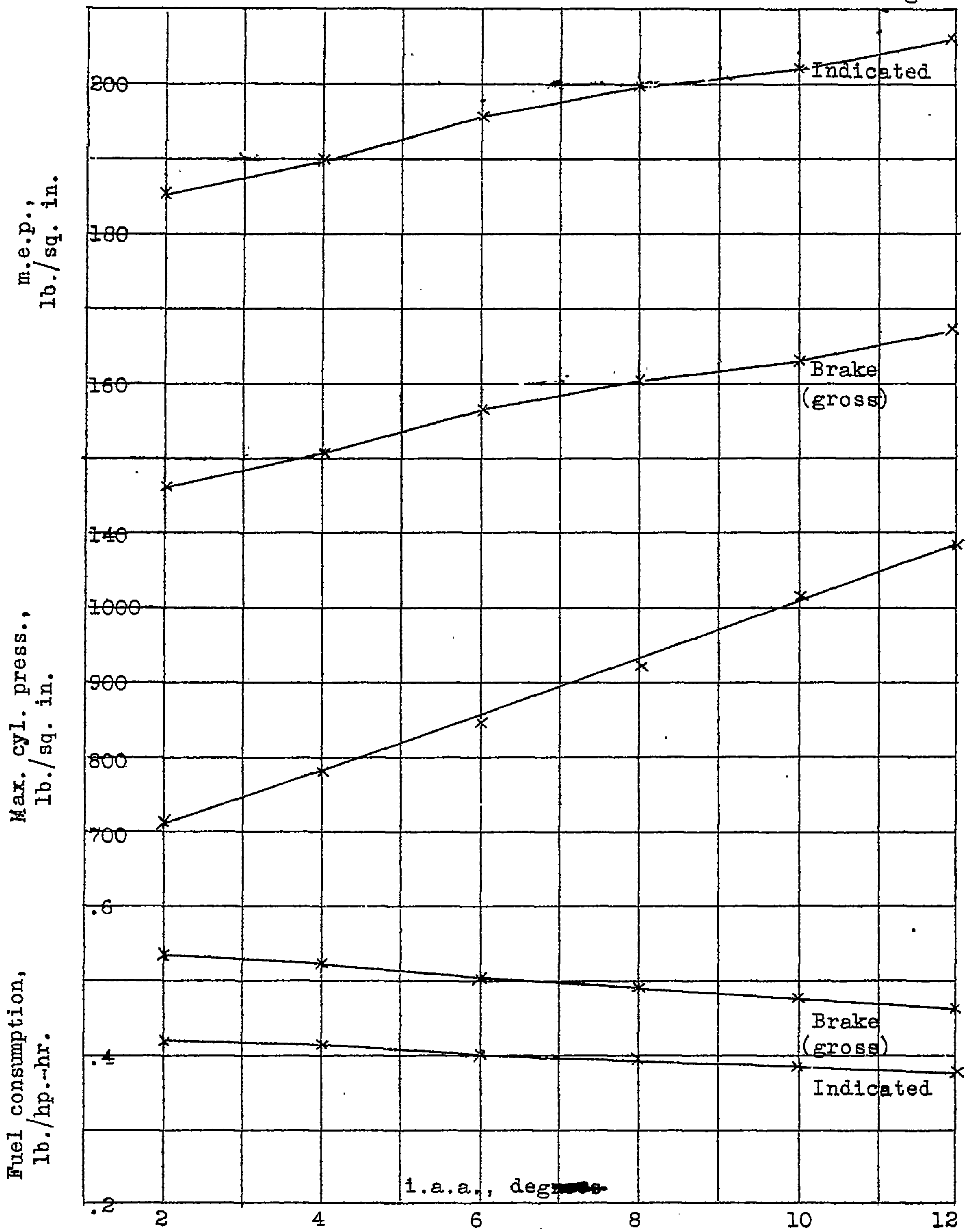



Figure 7.- Effect of injection advance angle on engine performance. 2000 r.p.m.; 7.5 inches Hg boost pressure; air-fuel ratio, 14.5.

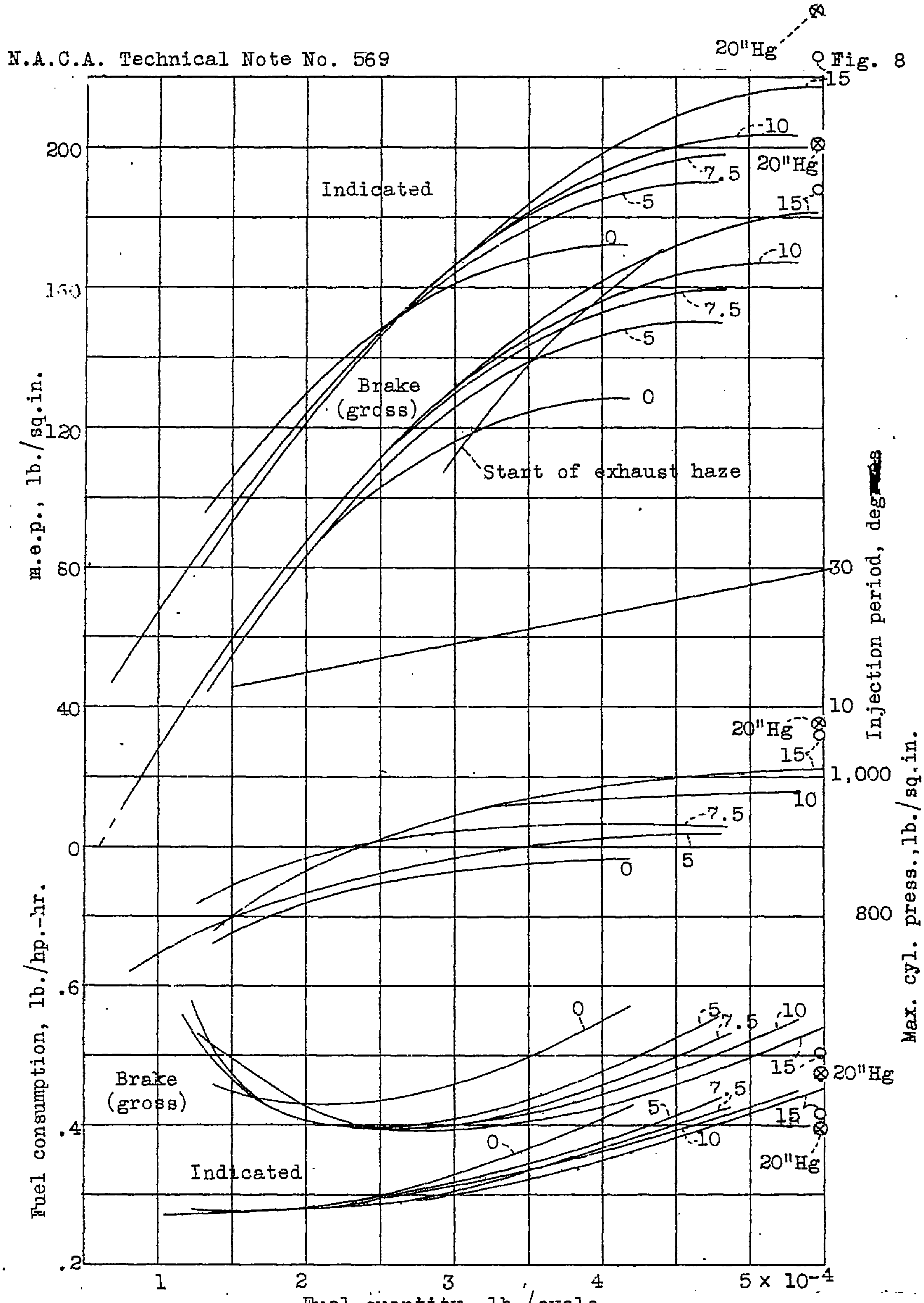



Figure 8.- Boosted engine performance; 2,000 r.p.m.; compression ratio, 14.6

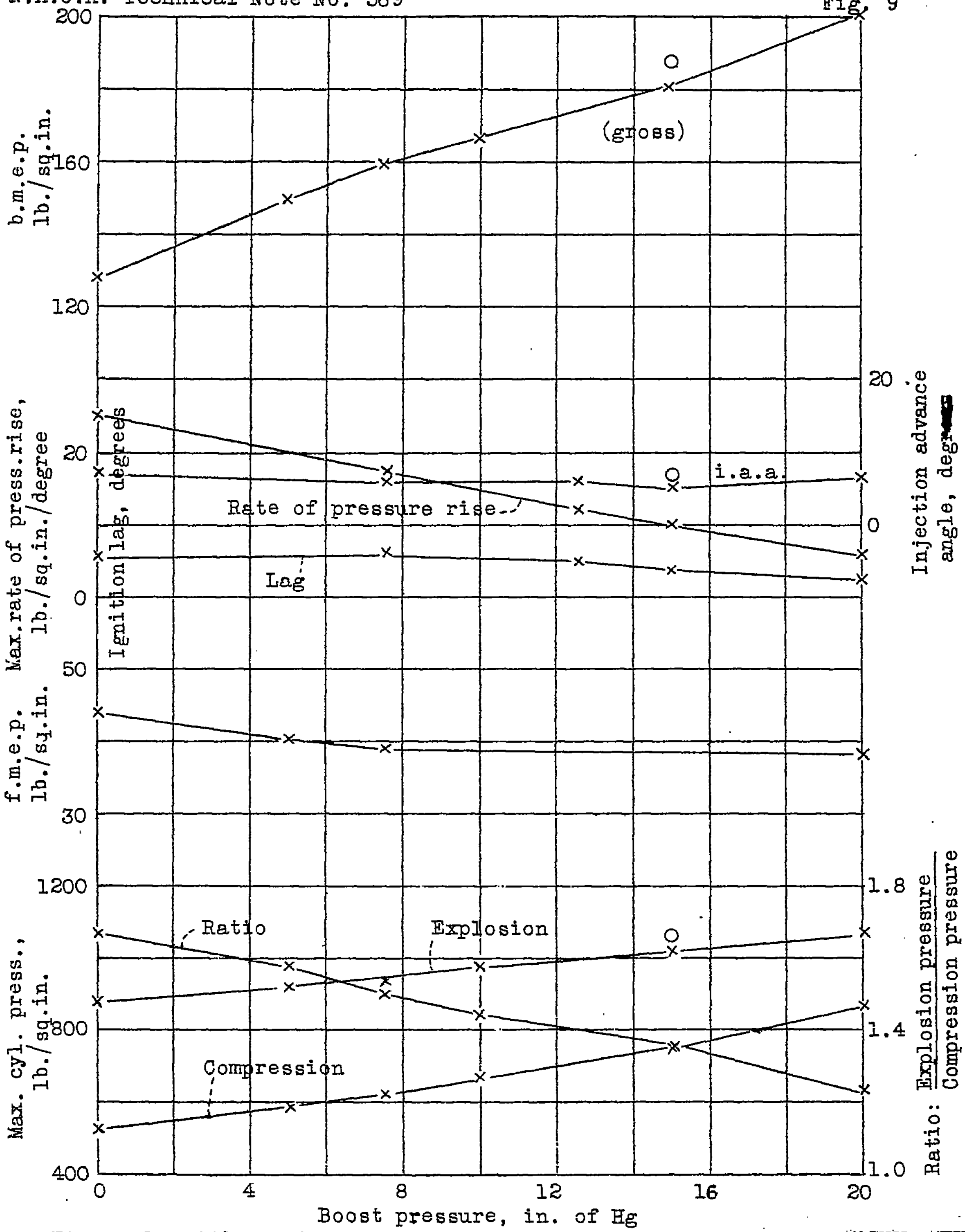



Figure 9.- Effect of boost pressure on performance; 2,000 r.p.m.; air-fuel ratio 14.5; compression ratio 14.6

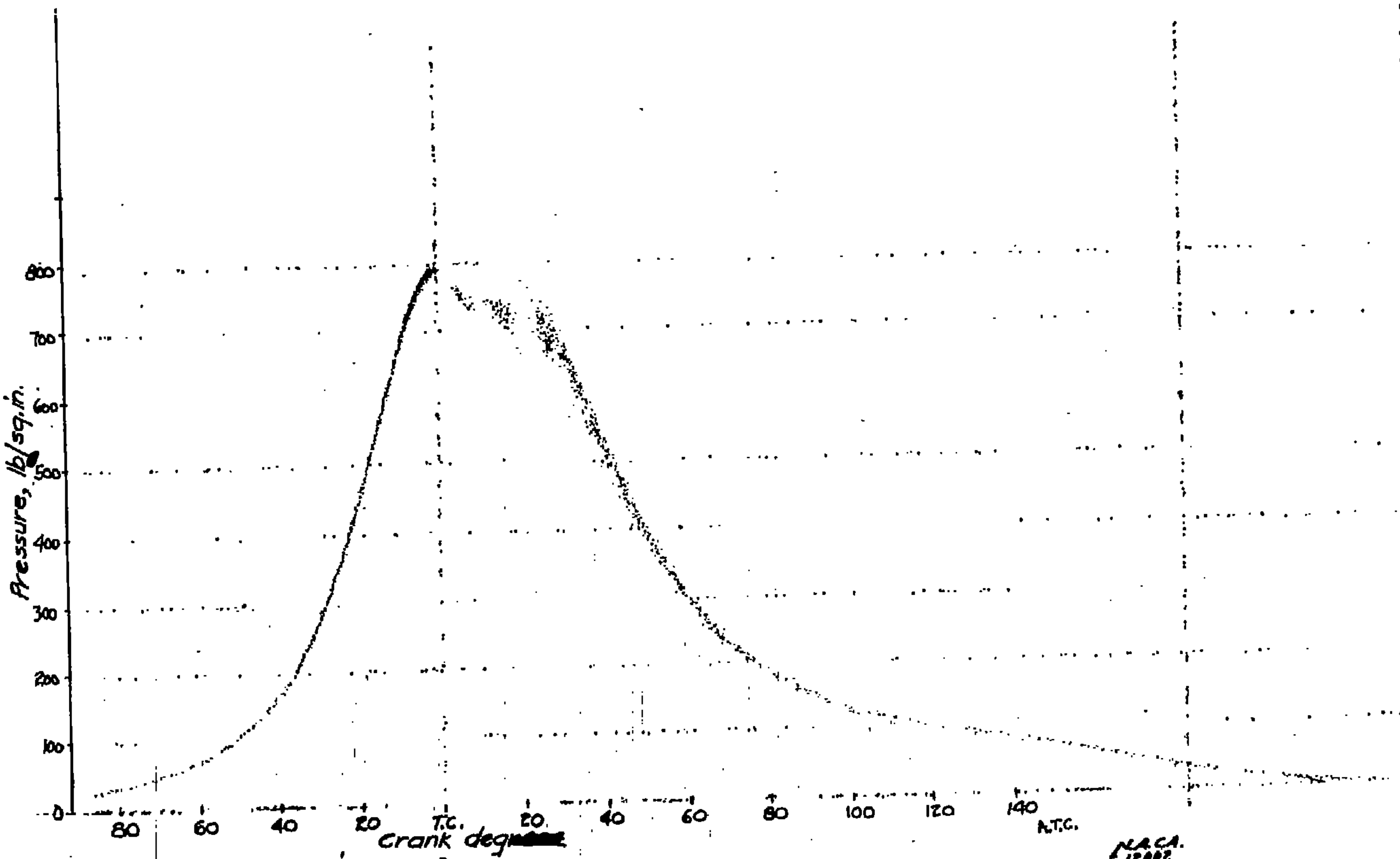
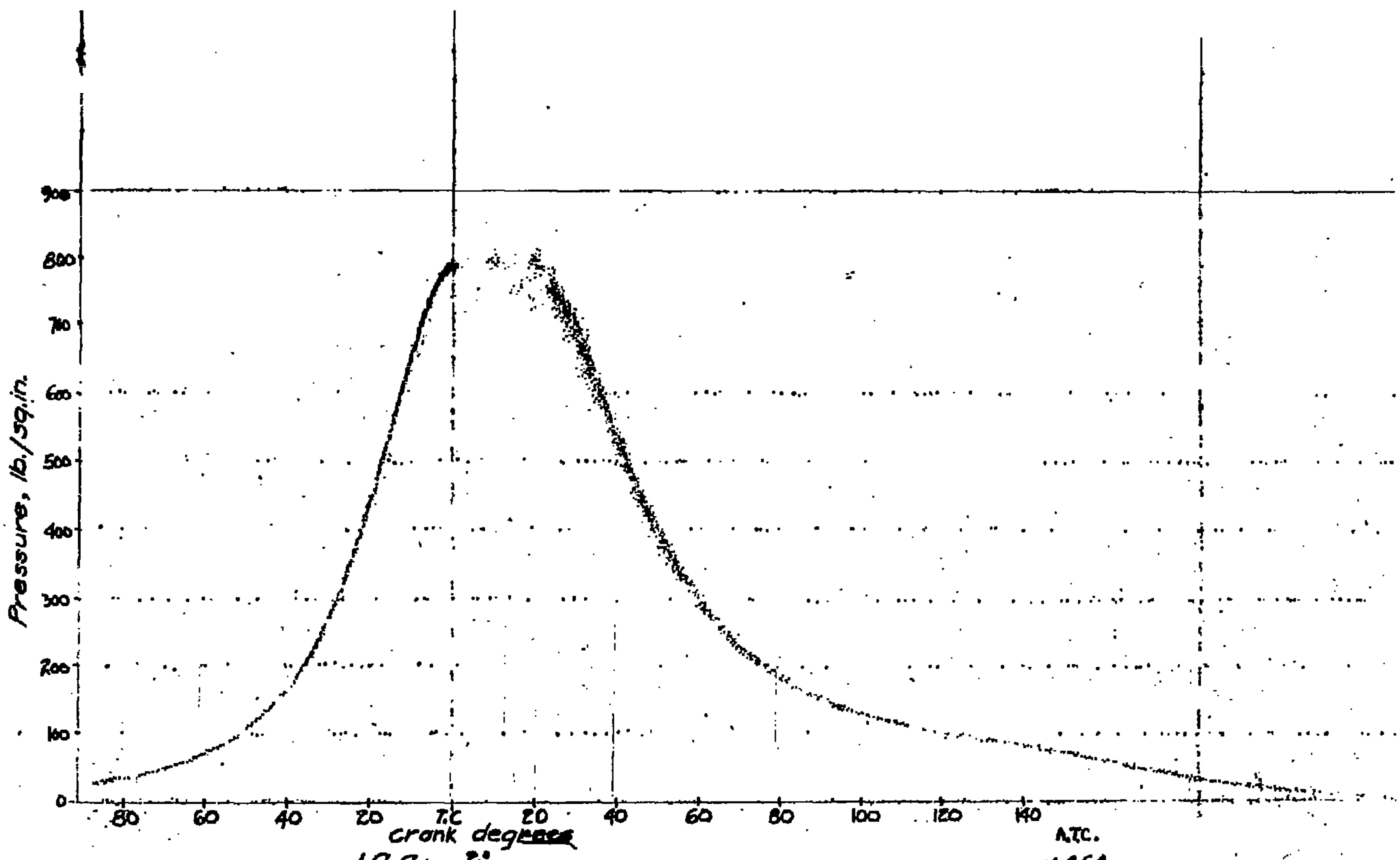

Pressure, lb/sq.in.
800
700
600
500
400
300
200
100
0
80
60
40
20
T.C.
20
40
60
80
100
120
140
A.T.C.
i.a.a. 0°
N.A.C.A.
12002

Figure 10 a


Pressure, lb./sq.in.
900
800
700
600
500
400
300
200
100
0
80
60
40
20
T.C
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40
60
80
100
120
140
A.T.C.
crank degrees

Figure 10b

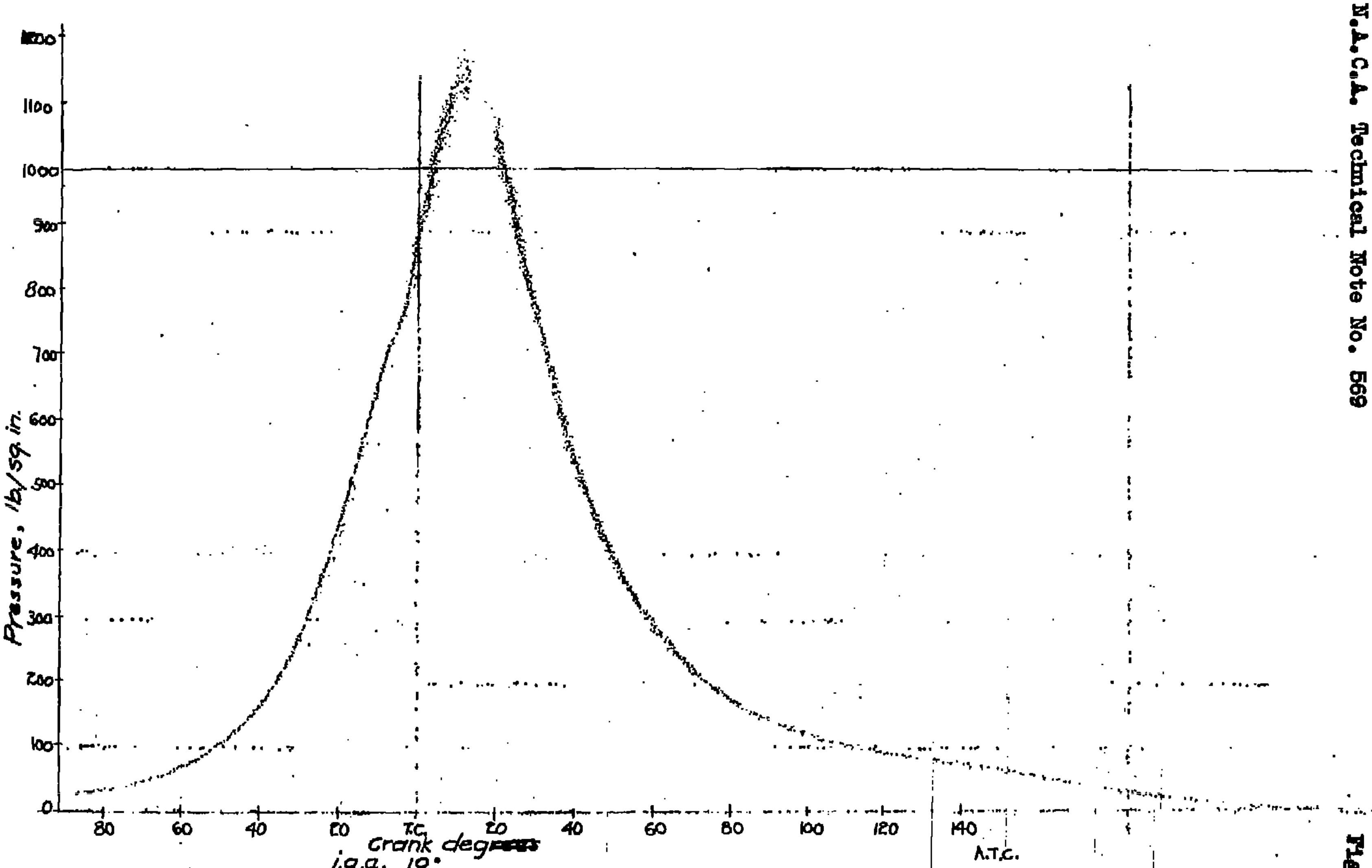


Figure 10c.- Indicator card. 2,000 r.p.m.; 7.5 in. Hg boost pressure; c.r.,15.2; air fuel ratio, 14